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# (54) Heat transfer apparatus

(57) A reversible capillary pumped heat transfer loop for transferring heat between first and second locations (2,3) and comprising, at each location, a heat transfer unit (1) for evaporating a working fluid when the unit is required to remove heat and for condensing the working fluid when the unit is required to deliver heat, each such unit (1) including a capillary device (19,20) and one or more channels (10) associated with the capillary device for the collection of fluid from it when the unit is acting as an evaporator and for the feeding of fluid to it when the unit is acting as a condenser whereby each unit comprises a fluid reservoir (18) into which the capillary device extends, the combined volumes of the reservoirs and the amount of working fluid in the loop being selected to ensure that there is always sufficient liquid in the reservoir to keep the capillary devices saturated with liquid.

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**Description**

**[0001]** This invention relates to a heat transfer apparatus. It arose in connection with the design of earth orbiting satellites where there is a need to transfer heat from one hot side, facing the sun, to an opposite, cold side. This can be done with the use of one or more evaporators for a working fluid at the hot side and one or more condensers located at the cold side, the evaporators and condensers being connected in a loop essentially as described with reference to Figure 1 of French patent specification FR 2723187. It is to be noted that such systems need to be designed so that they will operate in a gravity-free environment.

**[0002]** Rotation of the satellite can be expected to result in different sides of the satellite facing the sun at different times. It is therefore necessary to provide duplicate heat transfer systems designed to operate in opposite directions. However, such need for duplication also duplicates the weight. This is a problem because any weight added to the infrastructure of the satellite will reduce the maximum possible weight of its payload. Another problem arises from the fact that two separate heat pipe loops require twice the interface surface for heat collection and dissipation and there may be insufficient space available for this. Yet another problem is that two heat pipe loops require twice the amount of working fluid which may be toxic and corrosive giving rise to problems during manufacture and if there is leakage.

**[0003]** French patent specification 2723187 describes a technique for avoiding the need to duplicate the heat transfer systems. It describes, with reference to Figures 2-6, a capillary pumped heat transfer apparatus which is reversible. Using a single loop, heat is automatically transferred in a direction from a hot location to a cold location. However, although the desired effect is achieved using just one loop, the amount and therefore weight of components in that loop is not much less than what would be required in duplicate systems. This is because the system needs to contain an evaporator and a condenser at the hot location and also at the cold location. The evaporator, at the location which is for the time being cold, is essentially redundant, as is the condenser at the location which is, for the time being, hot.

**[0004]** French patent specification 2723187 does envisage the possibility of its evaporators also acting as condensers but, so far as the inventors know, no such system has been tried in practice.

**[0005]** Patent specification WO 97/00416 describes a capillary pumped heat transfer loop having a bank of evaporators connected in parallel at a hot location from which heat is to be removed. Thermally separated from the evaporators is a reservoir to which each of the evaporators is connected by a capillary link. This ensures that the capillary wick in the evaporator is continuously fed with liquid for evaporation.

**[0006]** The inventors have now recognized that an unexpected advantage can be obtained by using a capillary link, similar in function to that of WO 97/00416, in a reversible system. The advantage is that, when one of the units is being used (or starts to be used) as a condenser, the capillary link ensures that the wick is saturated with liquid and therefore does not tend to create an unwanted capillary pumping action in opposition to the wanted pumping action of the unit or units at the hot location. To obtain this effect it is necessary, of course, to include a reservoir at both locations.

**[0007]** Thus, according to this invention, there is provided a reversible capillary pumped heat transfer loop for transferring heat between first and second locations and comprising, at each location, a heat transfer unit for evaporating a working fluid when the unit is required to remove heat and for condensing the working fluid when the unit is required to deliver heat, each such unit including a capillary device and one or more channels associated with the capillary device for the collection of fluid from it when the unit is acting as an evaporator and for the feeding of fluid to it when the unit is acting as a condenser; characterized in that each unit comprises a fluid reservoir into which the capillary device extends, the combined volumes of the reservoirs and the amount of working fluid in the loop being selected to ensure that there is always sufficient liquid in the reservoir to keep the capillary devices saturated with liquid.

**[0008]** By ensuring that the loop contains the correct total amount of working fluid, it is possible to arrange for sufficient liquid always to be present in the reservoirs to keep the capillary devices primed with liquid. At the hot location, bubbles of gas will tend to collect in the reservoir where there is also plenty of liquid present. There is therefore relatively little chance of the gas bubbles entering into the capillary material. Instead, the capillary action will effectively reject the introduction of gas in favour of the absorption of liquid. At the cold location, saturation of the capillary device with liquid from the reservoir will ensure that it is hydrostatically passive, i.e. it produces no unwanted capillary pumping action.

**[0009]** Each unit preferably includes a tubular housing of heat conducting material defining the aforementioned channels, which open onto an inner surface of the housing. This allows heat to be readily conducted away from vapour in the channels when the unit is operating as a condenser. The channels are preferably formed at a first end of the housing whilst the other, second, end of the housing defines the reservoir. The heat conducting material of the housing is preferably a metal alloy since this allows the channels to be formed by an extrusion process and also helps to reduce weight. In a preferred arrangement, the capillary device is also of generally tubular configuration and fits in the housing in contact with its inner surface at least at the aforementioned "first" end.

**[0010]** The capillary device can be made from a single element but preferably takes the form of a capillary wick of relatively fine capillary structure to generate the

pumping action; and a separate capillary link, having a relatively coarse capillary structure, for supplying liquid from the reservoir to the wick. In such an arrangement the capillary link is preferably made from synthetic plastics material, for example polyethylene. An advantage of this is that it has a relatively low thermal conductivity and therefore helps to isolate the reservoir thermally from the source of heat. Another advantage is that synthetic plastics is relatively light compared with alternative materials such as stainless steel. The capillary material is arranged to line (or at least partially line) an inner surface of the reservoir so as to provide further thermal insulation of the contents of the reservoir.

**[0011]** The idea of using a capillary link in this way for thermal isolation purposes can be of benefit in evaporator units irrespective of whether they are required also to act as condensers, and thus there is a second aspect to this invention as set out in the next paragraph.

**[0012]** According to the second aspect of this invention, there is provided an evaporator for use in a capillary pumped heat transfer system comprising a reservoir, a capillary wick for providing a capillary pumping action, means for supplying heat to the wick to cause evaporation of liquid contained in it, and a capillary link arranged to feed liquid from the reservoir to the wick characterized in that the capillary link at least partially lines a surface of the reservoir.

**[0013]** The capillary link can be machined from a body of sintered powder, e.g. polyethylene powder, its external surfaces being shaped so as to make close resilient contact with internal surfaces of the reservoir and of the capillary wick.

**[0014]** In a preferred arrangement the capillary wick is also formed with a central aperture or bore defining a passage from the reservoir into the part of the housing that contains the wick. In this arrangement an inlet pipe for liquid from the condenser passes from one end of the housing, through the reservoir and well into the capillary link, preferably to the other end of the housing so that liquid leaving an open end of the inlet pipe flows in a reverse direction along the aforementioned bore before being absorbed into the capillary material. This reverse flow helps any bubbles of gas to drift towards the reservoir. Also, the fact that the inlet pipe needs to be of relatively small diameter causes a high velocity of flow through it, reducing any heating effect, and consequential generation of bubbles, as it passes through the reservoir.

**[0015]** The benefits of the inlet pipe referred to above can be useful independently of the first and second aspects of the invention previously described, and thus there is a third aspect to this invention as set out in the next paragraph.

**[0016]** According to the third aspect of this invention there is provided an evaporator for use in a capillary pumped heat transfer system comprising a capillary wick having an outer surface from which vaporized liquid is drawn by capillary action into the wick, and a reservoir characterized by means for introducing liquid into an end of the cavity remote from the reservoir so that at least some of the liquid passes along the cavity towards the reservoir before being absorbed into the wick.

**[0017]** An embodiment of the invention will now be described by way of example with reference to the accompanying drawings, in which:-

Figure 1 illustrates a reversible, capillary pumped heat transfer loop comprising two units, each constructed in accordance with the invention and designed to be located at different sides of a spacecraft so as to transfer heat from that location which is hotter to the location which is colder;

Figure 2 is a cross-section through the line II-II of Figure 1; and

Figure 3 is a detailed view, on a larger scale, of two of the channels indicated by reference numeral 10 on Figure 2. For the purposes of explanation, the parts on the left hand side of the line X of Figure 3 are illustrated acting as an evaporator whilst the parts on the right hand side are illustrated acting as a condenser. It is to be understood that in practice all the channels will serve at any one time either for evaporation or for condensation.

**[0018]** The illustrated heat transfer system comprises two units 1 located at first and second locations 2 and 3 respectively, as shown in Figure 1. The units 1 are identical, so only one will be described. This comprises a body 4 of metal chosen for its heat conducting properties and ease of extrusion. It has a generally tubular configuration having a first end defining a first port 5 and a second end having a second port 6 located in a threaded plug 7. The tubular housing 4 has a part 8 of relatively small diameter and which carries a flange 9 serving as a mechanical support and to transfer heat to and from a part or component of the spacecraft. On an inner surface of the portion 8, a large number of grooves 10 are formed as shown in Figure 2. These grooves extend parallel to the axis of the body 4.

**[0019]** The configuration of the grooves is best seen with reference to Figure 3 and is designed so that the grooves can be made by extrusion or by spark erosion. Each groove has an open side 11 having a width which is slightly less than half the width of the flats 12 between adjacent grooves.

**[0020]** Diverging from the open side 11 are two planar side walls 13. These define tangents at points P with a concave bottom surface 14 of circular cross-section. Thus, the surfaces 13 and 14 merge into each other continuously without any sharp corner.

**[0021]** Referring back to Figure 1, an internal bore of the body 4 is machined to define internal shoulders 15, 16 and 17. The shoulder 17 forms an acute angle with the axis of the body 4 and is aligned with a correspond-

ing shoulder 17A on the external surface of the body 4. The shoulders 17, 17A divide a small diameter part 8 at one end the body 4 from a larger diameter part 18 at the opposite end. This wider part 18 serves as a reservoir for working fluid. Its volume is greater than the volume of the narrower part 8 of the body 4 and the total volumes of all reservoirs in the loop accounts for more than half of the volume of fluid in the loop.

**[0022]** Contained within the body 4 is a capillary device formed from two separate tubular bodies 19, 20. The body 19, which will be referred to as the "wick", defines relatively fine capillary ducts so as to create a strong capillary pumping action. In the illustrated embodiment it is constructed from PTFE powder which is sintered to form a porous rigid body having a pore size of about 2.5 µm. Other suitable materials include: sintered metal e.g. copper, stainless steel wire, molybdenum, tungsten, titanium or nickel; sintered ceramics; and many forms of open cell, foamed or sintered thermoplastic materials which may be glass-filled and/or powder filled. The purpose of filling the plastics material is to decrease the thermal expansion coefficient of the material and to increase the Young's modulus. Another powdered material may be introduced to increase the porosity of the wick; this powder may be removed, after sintering, by a post-burning process.

**[0023]** The wick 19 is machined to the required shape. It has a shoulder 21 on its external surface which engages against the shoulder 15 on the internal surface of the body 4 to locate it in a desired axial position. The internal bore of the wick 19 is flared outwardly at its open end to co-operate with a tapered ferrule 22. An externally threaded plug 23 co-operates with an internal thread of the body 4 between the shoulders 16 and 17 so as to exert axial pressure on the ferrule 22, thereby pressing the porous wick 19 into a fluid tight contact with the internal wall of the body 4.

**[0024]** The capillary link 20 is, in the illustrated example, made in a way similar to that of the wick 19 but from sintered polyethylene powder and has a pore size of about 105 µm so that it defines relatively coarse capillary passages. It has a relatively narrow part 24 which fits tightly into the body 19, because of the natural elasticity of the synthetic plastics materials, and extends from an open end to a shoulder 26 which is located against the shoulder 17 of the body 4. The shoulder 26 leads to a wide part 25 of the link 20 which is located against the internal wall of the wide part of the body 4. The link 20 is held axially in position by the plug 7.

**[0025]** In alternative constructions the capillary link 20 could be made from other synthetic plastics materials, possibly glass-filled.

**[0026]** The plug 7 also supports a pipe 27 which extends along the axis of the body 4 connecting the port 6 to a point close to the open end of the capillary link 20. Its outer diameter is significantly smaller than the inner diameter of the narrow part of the link 20 so as to allow the passage of fluid therebetween. It is held in its axial position by kinks making contact with the inner surface of the link 20 so as to space the pipe 27 from that inner surface.

**[0027]** Operation of the system will now be described, assuming a start-up condition where everything is at the same temperature. The amount of working fluid, which is ammonia in the illustrated system, is sufficient to ensure that, within a wide range of normal temperatures, there is always sufficient liquid in the reservoirs 18 to saturate the capillary bodies 19 and 20 with liquid.

**[0028]** Assume that location 2 becomes hotter than location 3. Heat is transmitted from the heat source, through flange 9, to the flats 12 defined on fins between the grooves 10. The natural elasticity of the synthetic plastics material from which the wick 19 is constructed holds it in close contact with the flats 12 and heat is therefore readily conducted from the fins to the liquid in the capillary channels of the wick 19. This causes the liquid to evaporate under the fins at a region 28 close to the surface of the wick 19, as shown above the line 28A on the left hand side of Figure 3. Note that, on the Figures, areas occupied by liquid are shown with horizontal lines.

**[0029]** The vapour is collected, as indicated by the arrows on Figure 3, by the channels 10 and transmitted along them to the port 5. By capillary pumping, more liquid is introduced into the capillary wick 19 from the capillary link 20; and into the capillary link 20 either directly from the pipe 27 or from the reservoir 18. Because there is always sufficient liquid in the reservoir to saturate the capillary members, any bubbles of vapour inside the narrow part 24 of the link 20 will not be absorbed by it. Such bubbles will pass into the reservoir where, being cooler, they may condense. The link 20 in this way acts as a simple heat pipe between the relatively hot flange 9 and the cooler reservoir 18. It maintains a flow of liquid towards the fine capillary wick 19 and helps to move gas bubbles in the direction of the reservoir, this latter effect acting in concert with the flow of liquid from pipe 27 (to be described later).

**[0030]** The temperature of the reservoir 18 at the hot location defines the saturation temperature of the working fluid and therefore needs to be controlled. In the illustrated apparatus the temperature is self-controlled by a balance of parasitic heat fluxes transferred: within the body 4; by the gas bubbles pushed towards the reservoir; by cold liquid coming from the condenser; and by external thermal leaks with the environment. A notable feature is that heat flow from the flange 9 to liquid in the reservoir is limited by the thermally insulating properties of the material from which the capillary link 20 is made. It provides a thermally insulating lining on the inner surface of the reservoir. In an alternative construction an active temperature control system could be included. This could employ heaters, Peltier cells, dedicated radiative surfaces, etc. The materials and construction of the apparatus would then need to be such as to minimise parasitic heat fluxes.

[0031] Vapour from the port 5 is transferred by the capillary pumping action along pipework to a corresponding port at location 3 where it enters the grooves 10. At the input end of each groove, its content is entirely vapour but this condenses progressively along the channel so that at the opposite end its content is entirely liquid. The situation close to the input end is shown at the right hand side of Figure 3, where it can be seen that a thin film C of condensed liquid has formed over the entire surface of the groove as heat is conducted from the vapour through this surface and into the conductive body 8. The uniformity of this thin film is a significant advantage as compared with previous designs of evaporator which have employed rectangular or dovetail shaped grooves having corners where the liquid tends to accumulate. In such a construction, the accumulation of liquid in the corners reduces the effective surface area through which heat from the vapour can be conducted away and increases the thickness of the film of liquid, which acts as an insulator between the vapour and the body 4 thereby impeding the transfer of heat.

[0032] In the illustrated design, the only corners effective to attract the liquid are those, shown at C, formed between the conductive metal body 8 and the capillary wick 19, so the surface area of metal in close thermal contact with the vapour is as high as possible and so that the liquid, after condensation from the vapour, is removed as quickly as possible from this surface. The liquid passes into the wick which is entirely saturated with liquid because its temperature, like that of the body part 8, is cooler than the saturation temperature of the fluid. Therefore, there can be no capillary action of the elements 19 or 20, these being entirely passive when the apparatus is acting as a condenser. Thus, the condenser is hydraulically passive: fluid flows through it only because it is pushed by the pressure generated by the evaporator.

[0033] The condensed liquid is pushed into the reservoir or passes directly into the pipe 27 from where it passes to the port 6 of the unit at location 2. The small diameter of the pipe 27 ensures that this liquid passes through the relatively hot reservoir at a relatively high velocity, thereby minimising the opportunity for it to evaporate. The risk of bubbles entering the capillary elements of the evaporator is thus considerably reduced and any such bubbles that do form tend to be carried by the reverse flow of liquid from the open end of the pipe 27 towards the reservoir.

[0034] On reversal of the temperature differential between the devices 1, their roles are automatically reversed, the element 20 quickly ensuring that the micropores of the element 19 stay or become saturated with liquid.

## Claims

1. A reversible capillary pumped heat transfer loop for transferring heat between first and second locations (2, 3) and comprising, at each location, a heat transfer unit (1) for evaporating a working fluid when the unit is required to remove heat and for condensing the working fluid when the unit is required to deliver heat, each such unit (1) including a capillary device (19, 20) and one or more channels (10) associated with the capillary device for the collection of fluid from it when the unit is acting as an evaporator and for the feeding of fluid to it when the unit is acting as a condenser; characterized in that each unit comprises a fluid reservoir (18) into which the capillary device extends, the combined volumes of the reservoirs and the amount of working fluid in the loop being selected to ensure that there is always sufficient liquid in the reservoir to keep the capillary devices saturated with liquid.

2. Apparatus according to claim 1 comprising a tubular housing (4) in which the capillary device is located, the channel or channels (10) being defined between the housing (4) and the capillary device (19, 20); and the reservoir (18) being defined by one end of the housing (4).

3. Apparatus according to claim 2 in which the tubular housing has a portion (18) of enlarged diameter defining the reservoir.

4. Apparatus according to claim 2 or 3 in which the capillary device includes a tubular body of absorbent material having an axis which extends in the same direction as an axis of the tubular housing.

5. Apparatus according to claim 4 in which the capillary device comprises a wick (19) of absorbent material having relatively fine capillary ducts to provide pumping pressure for the fluid when the apparatus is acting as an evaporator and a capillary link (20) of absorbent material having relatively coarse capillary ducts and serving as means for feeding liquid from the reservoir (18) to the wick (19).

6. Apparatus according to claim 5 in which the capillary link (20) is a rigid preformed member.

7. Apparatus according to claim 5 or 6 in which the wick (19) and the capillary link (20) are both tubular, the capillary link (20) having a relatively narrow portion (24) which fits inside the wick (19) and having a relatively wide portion (25) which resides in the reservoir (18).

8. Apparatus according to claim 5, 6 or 7 comprising an annular clamping device (22, 23) forming a seal between the reservoir (19) and the channel or channels (10).

**9.** Apparatus according to claim 8 in which the capillary link (20) passes through the annular clamping device (22, 23).

**10.** Apparatus according to any of claims 5 to 9 comprising a pipe (27) extending from a first port (6) at one end of the tubular housing, through the reservoir (8) and through the capillary link (20) for the supply of liquid to the capillary device (19, 20) at an end remote from the reservoir.

**11.** Apparatus according to claim 10 comprising a second port (5) at the opposite end of the tubular housing (4) and communicating with the or each channel (10).

**12.** Apparatus according to any of claims 2 to 11 comprising a number of channels defined by grooves extending along an inside surface (12) of the tubular member.

**13.** Apparatus according to claim 12 in which the grooves are formed by extrusion or spark erosion.

**14.** Apparatus according to any preceding claim in which the amount of fluid in the loop is sufficient to ensure that there is a store of liquid in the reservoirs (18) at all normal operating temperatures of the system.

**15.** An evaporator for use in a capillary pumped heat transfer system comprising a reservoir (18), a capillary wick (19) for providing a capillary pumping action, means (8, 9) for supplying heat to the wick to cause evaporation of liquid contained in it, and a capillary link (20) arranged to feed liquid from the reservoir (18) to the wick (19) characterized in that the capillary link (20) at least partially lines a surface of the reservoir (18).

**16.** An evaporator according to claim 15 characterized by a housing (4) having a first portion (8) containing the capillary wick (19) and serving as the means for supplying heat to the wick and a second portion (18) defining the reservoir.

**17.** An evaporator according to claim 15 or 16 characterized in that the capillary link (20) is made of synthetic plastics material.

**18.** An evaporator according to claim 15, 16 or 17 in which the capillary link (20) extends into the wick (19).

**19.** An evaporator according to any one of claims 15 to 18 in which the capillary link (20) is machined so as to make a contact fit with internal surfaces of the wick (19) and the reservoir (18).

**20.** An evaporator according to claim 18 or 19 in which the capillary link (20) is tubular and in which the evaporator comprises an inlet duct (27) for liquid extending through the reservoir (18) and the capillary link (20) to an open end arranged so that liquid issuing from it flows back towards the reservoir.

**21.** An evaporator according to any one claims 15 to 20 in which the capillary link (20) is made of sintered powder.

**22.** An evaporator for use in a capillary pumped heat transfer system comprising a capillary wick (19) having an outer surface from which vaporized liquid is drawn by capillary action into the wick, and a reservoir (18) characterized by means (27) for introducing liquid into an end of the cavity remote from the reservoir (18) so that at least some of the liquid passes along the cavity towards the reservoir before being absorbed into the wick (19).

**23.** An evaporator according to claim 22 characterized in that the means for introducing liquid comprises a pipe (27) extending from an inlet end, through the cavity to an outlet end.

**24.** An evaporator according to claim 23 characterized in that the pipe (27) extends through the reservoir (18) before passing through the cavity in the wick (19).

**25.** An evaporator according to any of claims 22 to 24 comprising a capillary link (20) for feeding liquid from the reservoir (19) to an internal surface defining the cavity of the wick (19).

**26.** An evaporator according to claim 25 characterized in that the capillary link (20) is a tubular body having a relatively narrow portion fitting inside the cavity of the wick and a relatively wide portion fitting against an inner surface of the reservoir (18).

**27.** An evaporator according to claim 26 including means for spacing the pipe from an inner surface of the capillary link.

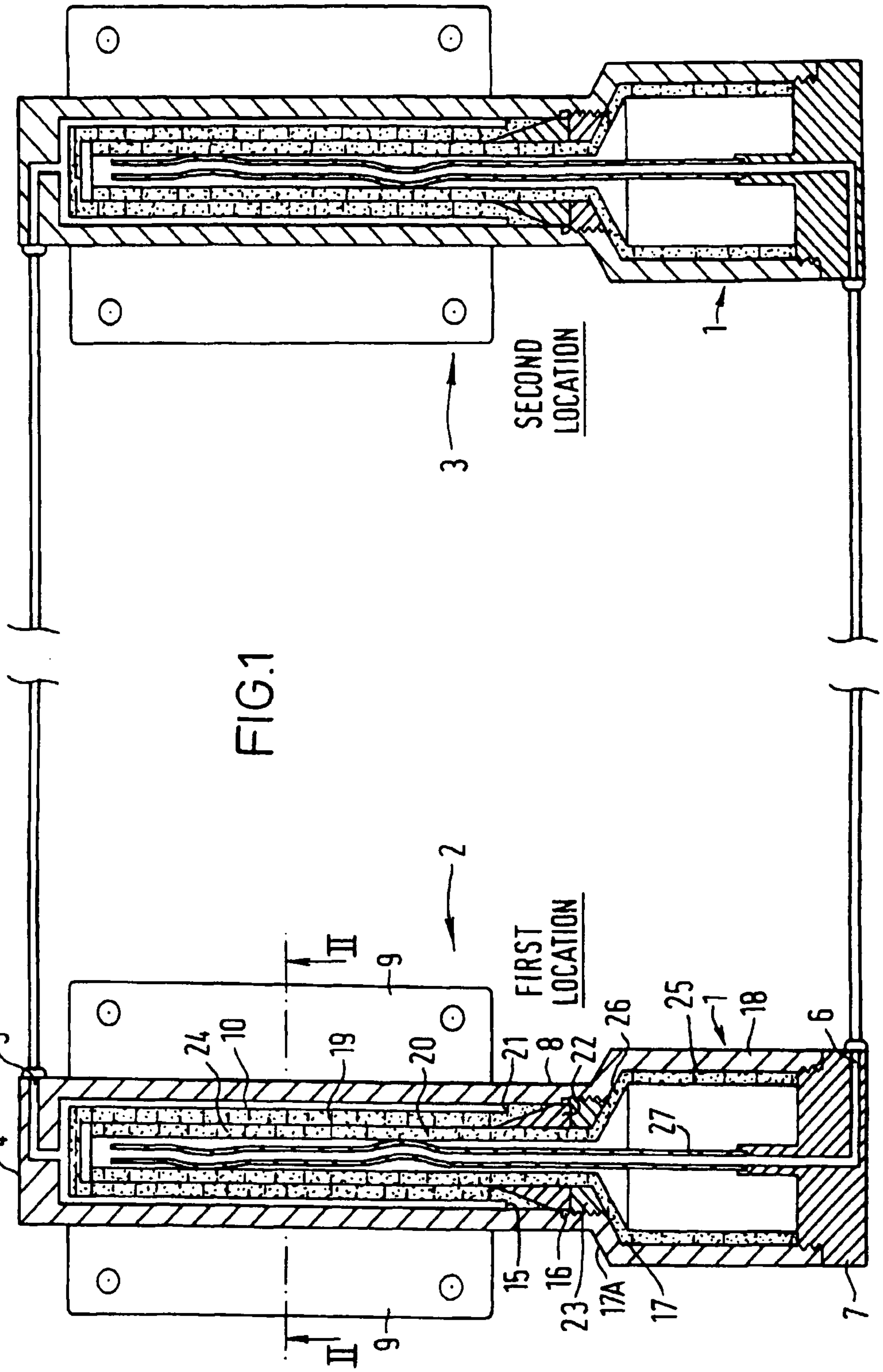
FIRST LOCATION
SECOND LOCATION
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FIG.1

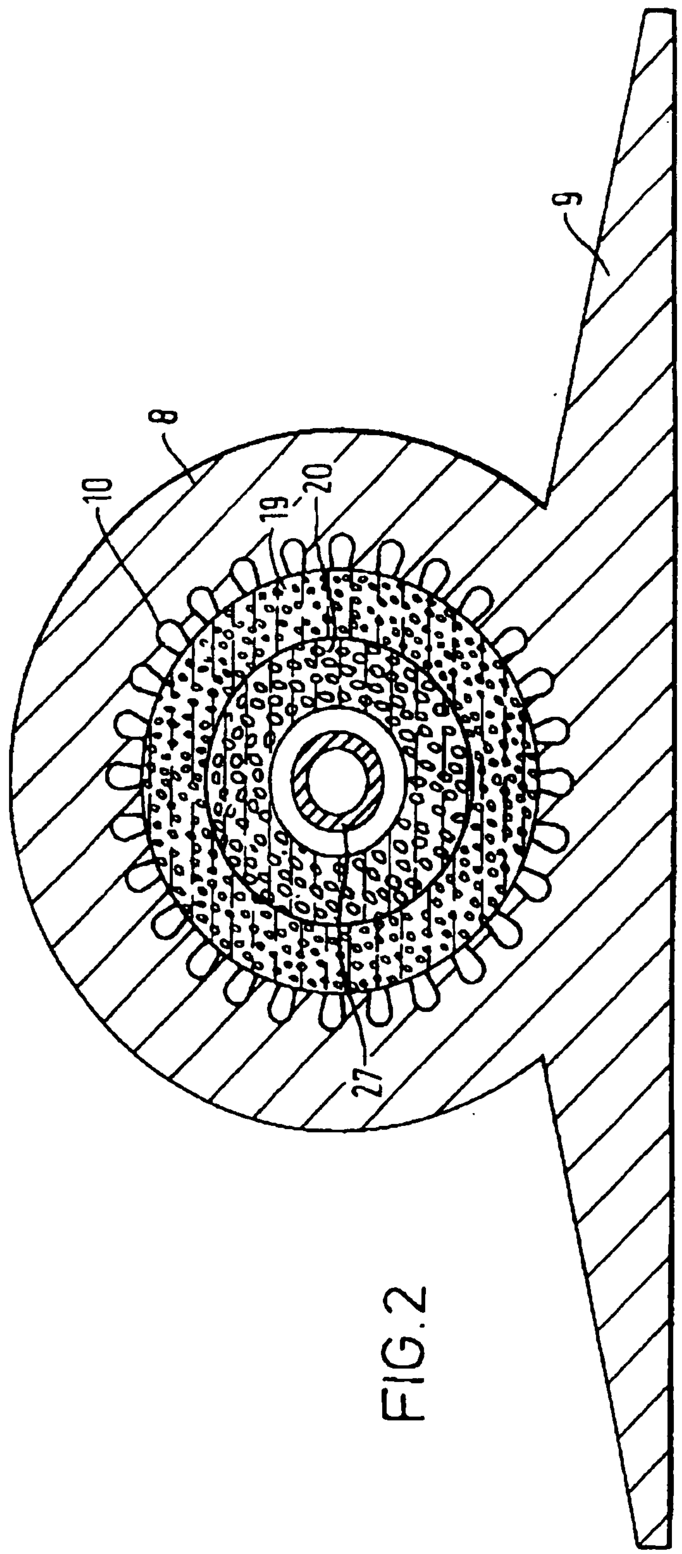


FIG.2

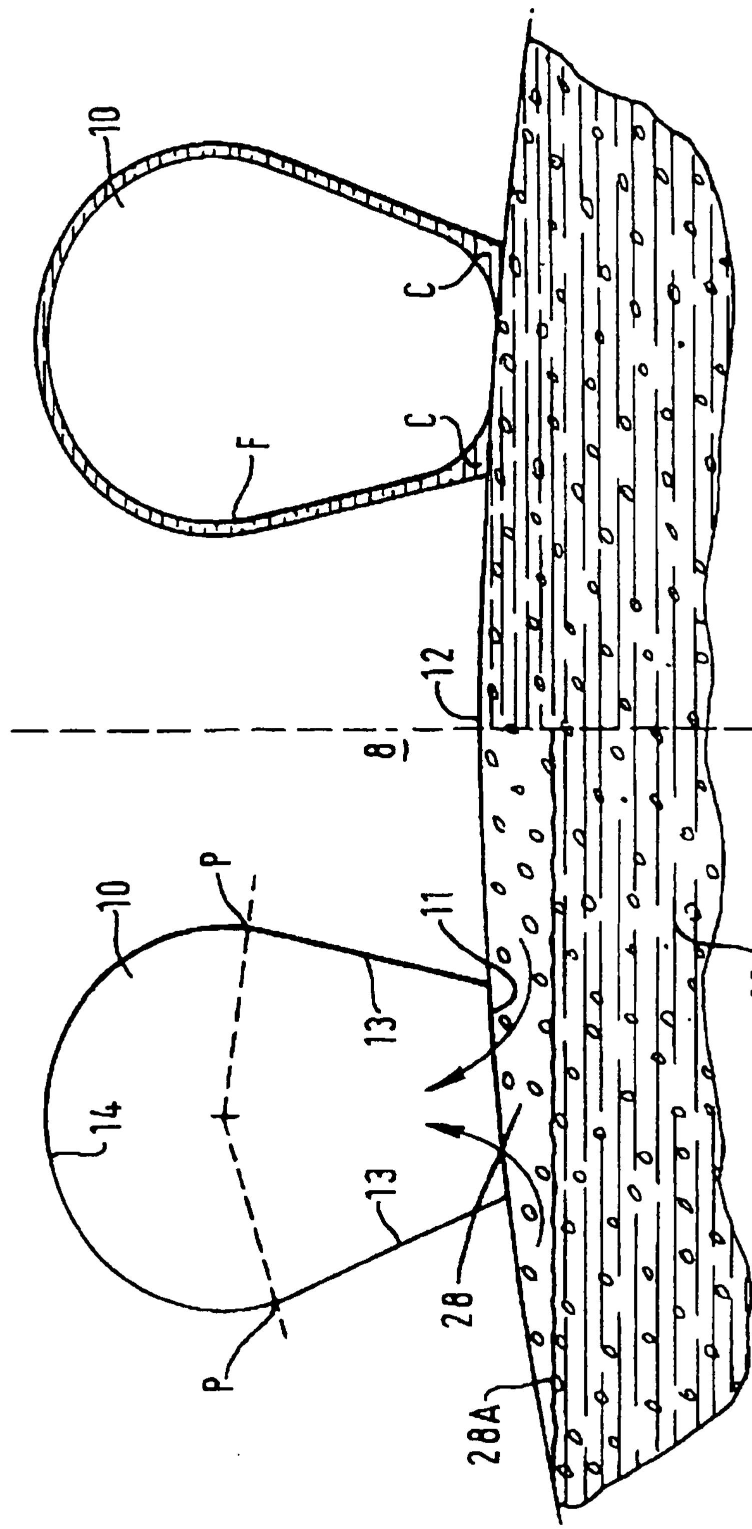


FIG. 3.

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# EUROPEAN SEARCH REPORT

Application Number
EP 99 30 7326

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The present search report has been drawn up for all claims

| Place of search | Date of completion of the search | Examiner |
|---|---|---|
| THE HAGUE | 16 December 1999 | Beltzung, F |

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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D : document cited in the application
L : document cited for other reasons

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# EUROPEAN SEARCH REPORT

Application Number
EP 99 30 7326

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## ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 99 30 7326

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
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